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Twenty-one articles were published during the 4-year duration of the Army Research Office Grant DAAG29-85-K-0025, "Nonlinear Surface Polaritons," and at least one more is in the process of being written. Among the highlights of the research conducted with the support of this grant we mention the first exact solutions for the dispersion curves of p-polarized nonlinear surface polaritons, on a nonlinear dielectric characterized by a Kerr-like dielectric constant (Refs. 2, 3*); the first deviation of surface polariton (envelope) solitons associated with nonlinear guided electromagnetic waves (Ref. 5); studies of the guiding of linear, p-polarized surface polaritons by the change in the index of refraction on a nonlinear dielectric medium caused by an intense, s-polarized surface polariton (Ref. 9); The explanation for the k-gaps (as opposed to w-gaps) observed in some dispersion curves of surface polaritons on metallic gratings as determined by reflectivity measurements (Ref. 13); and contributions to the theory of the stability of nonlinear surface electromagnetic waves (Refs. 7, 8). In addition, we have studied nonlinear surface

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surface roughness; gratings, reflectivity; nonlinear waveguides; localization.

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and guided electromagnetic waves, on non-Kerr-like nonlinear dielectric media (Refs. 4, 12); we have investigated the existence and properties of nonlinear guided electromagnetic waves in layered media consisting of alternating layers of linear and nonlinear dielectric media (Refs. 16, 20); we have shown that a disordered surface can lead to the localization of a surface acoustic wave -- this appears to be the first demonstration of this effect (Ref. 17); and we have also provided evidence for the existence of nonstationary, nonlinear guided electromagnetic waves (Ref. 10).

*The references are to the attached list of papers published with the support of Army Research Office Grant DAAG29-85-K-0025.

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1. Nonlinear Waves Guided by the Interface of a non-Kerr-like medium, G. I. Stegeman, C. T. Seaton, J. Ariyasu and T. P. Shen, Opt. Commun. 56, 365 (1986).

2. Exact Theory of Nonlinear P-Polarized Optical Waves, A. D. Boardman, A. A. Maradudin, G. I. Stegeman, T. Twardowski, and E. M. Wright, Phys. Rev. A35, 1159 (1987).

3. Exact Dispersion Relations Solutions for TM-Polarized Guided Waves at a Nonlinear Interface," D. Mihalache, G. I. Stegeman, C. T. Seaton, E. M. Wright, R. Zanori, T. Twardowski, and A. D. Boardman, Opt. Lett. 12, 178 (1987)

4. Nonlinear Thin Film Guided Waves in Non-Kerr Media, C. T. Seaton, J. Ariyasu, G. I. Stegeman, and T. P. Shen, Appl. Phys. Lett. 47, 1254 (1985).

5. Surface Polariton Solitons, A. D. Boardman, G. S. Cooper, A. A. Maradudin, and T. P. Shen, Phys. Rev. B34, 8273-8278 (1986).

6. Power-Dependent Attenuation of Nonlinear Waves Guided by Thin Films, J. Ariyasu, C. T. Seaton, and G. I. Stegeman, Appl. Phys. Lett. 47, 355 (1985).

7. New Theoretical Developments in Nonlinear Guided Waves: Stability of TE_1 Branches, J. Ariyasu, C. T. Seaton, G. I. Stegeman, and J. V. Moloney, IEEE J. Quant. Electron. QE-22, 984 (1986).

8. Stability of Nonlinear Stationary Waves Guided by a Thin Film Bounded by Nonlinear Media, J. V. Moloney, J. Ariyasu, C. T. Seaton, and G. I. Stegeman, Appl. Phys. Lett. 48, 826 (1986).

9. Control of TM by Strong TE Nonlinear Guided Waves, T. P. Shen, G. I. Stegeman, and A. A. Maradudin, Appl. Phys. Lett. 52, 1-3 (1988).

10. Numerical Evidence for Non-Stationary Nonlinear Guided Waves, J. V. Moloney, J. Ariyasu, C. T. Seaton, and G. I. Stegeman, Opt. Lett. 11, 315 (1986).

11. Optical Interactions at Rough Surfaces, A. A. Maradudin, A. R. McGurn, R. S. Dummer, Zu Han Gu, A. Wirgin, and W. Zierau, in Laser Optics of Condensed Matter, eds. J. L. Birman, H. Z. Cummins, and A. A. Kaplyanskii (Plenum, New York, 1988), pp. 127-136.

12. New Theoretical Developments in Nonlinear Guided Waves: Non-Kerr-Like Media, G. I. Stegeman, E. M. Wright, C. T. Seaton, J. V. Moloney, T. P. Shen, A. A. Maradudin, and R. F. Wallis, IEEE J. Quant. Electron. QE-22, 977 (1986).

13. k-Gaps for Surface Polaritons on Gratings, V. Celli, P. Tran, A. A. Maradudin, and D. L. Mills, Phys. Rev. B37, 9089-9092 (1988).

14. Nonlinear Waves Guided by a Single Interface, G. I. Stegeman, C. T. Seaton, J. Ariyasu and A. A. Maradudin, J. Appl. Phys. 58, 2453 (1985)

15. Nonlinear Surface Polaritons Guided by Metal Surfaces, J. Ariyasu, C. T. Seaton, G. I. Stegeman, A. A. Maradudin, and R. F. Wallis, J. Appl. Phys. 58, 2460 (1985).

16. S-Polarized Guided and Surface Electromagnetic Waves Supported by a Nonlinear Dielectric Film, Wei Chen and A. A. Maradudin, J. Opt. Soc. Am. B5, 529-538 (1988).

17. Localization of Shear Horizontal Surface Acoustic Waves on a Disordered Surface, A. R. McGurn and A. A. Maradudin, Phys. Rev. B (in print).

18. Reflection and Transmission of Guided Waves at End Faces, T. P. Shen, R. F. Wallis, A. A. Maradudin, and G. I. Stegeman, JOSA B, in press.

19. Surface Polariton-Like Waves Guided by Thin, Lossy Metal Films, J. J. Burke, G. I. Stegeman, and T. Tamir, Phys. Rev. B33, 5186 (1986).

20. S-Polarized Optical Waves in Multilayer Nonlinear Waveguides with Positive Nonlinearities, Wei Chen and A. A. Maradudin, submitted to J. Opt. Soc. Am. B.

21. Fresnel-Like Behavior of Guided Waves, T. P. Shen, R. F. Wallis, A. A. Maradudin, and G. I. Stegeman, J. Opt. Soc. Am. A4, 2120-2132 (1987).

Exact theory of nonlinear p-polarized optical waves

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Exact calculations are presented of the properties of nonlinear p-polarized waves propagating along the plane boundary between a nonabsorbing, optically self-focusing, nonlinear dielectric and a nonabsorbing positive, or negative, linear dielectric. A nonlinear polarization is used that arises from a number of causes for both Kerr-like and non-Kerr-like saturating media. In the results given here the linear dielectric is a metal, if negative, and is glass if positive. It is found that the variation of the power flow along the guiding surface with effective index, for negative linear dielectrics, will always exhibit a maximum. For data corresponding to copper bounded by, for instance, a self-focusing nonlinear semiconductor, access to this maximum involves such a large change in the refractive index of the nonlinear material, that it is of no practical interest. In the visible better matching of the metal to a nonlinear material can, in principle, be achieved so this maximum may be reached for fairly modest nonlinear changes in the refractive index. A detailed comparison is made with approximations that are based upon a curtailed form of nonlinearity. At low frequencies, for modest nonlinear changes in the refractive index, the dependence of the power flow curve upon the effective guide index is fairly close to several of the earlier published theories. These include a well-known approximation in which the transverse field component is assumed to be dominant. The neighborhood of the maximum, and beyond, becomes accessible at higher operating frequencies and significant differences from earlier approximations may then occur. For positive linear dielectrics the exact theory shows a strong similarity to many more approximate ones, as expected, but the difference between the TM and TE surface wave behavior cannot be discounted. We present several sample calculations of the power flow together with detailed plots of the field components, the magnitude of the nonlinearity, the effect of nonlinearity, and the behavior of the first integral.

INTRODUCTION

During the recent upsurge of interest in nonlinear optical wave propagation in planar[1−7] and optical fiber[8] structures there has been a heavy emphasis on TE waves. For these, confidence can be placed in the form of nonlinear dielectric tensors used because, as was first shown a long time ago[2,9,10] the TE nonlinear differential equation for the electric field component has an elegant and exact analytical solution. This fact enables many benchmarks to be developed of both an analytical and numerical kind and encourages detailed solutions. For TM waves, however, the situation is quite different. For these types of nonlinear waves, as has been discussed recently,[11] a number of approximations[11−24] have been employed that limit the applicability of the results, quite often in a spectacular manner. This development has taken place against a background that contains a fairly old exact analytical calculation of the first integral of the guided-wave TM nonlinear equations.[25] The latter was obscurely presented, however, and in a context that is difficult to relate to in optics. It has, therefore, remained unexploited in the modern literature. The discussion of the relative importance of TM waves and whether their behavior can, in certain circumstances, be trivially inferred from the known behavior of TE waves, will be deferred until later in this article.

THEORY

For an isotropic material the nonlinear polarization can be expressed in terms of the fourth-rank susceptibility tensor X_{ijkl} which has 21 nonzero elements of which only three are independent:

Fresnel-like behavior of guided waves

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The reflection and transmission of thin-film guided waves incident at variable angles upon a variety of transverse discontinuities are analyzed. A thin film bounded by semi-infinite media is modeled by a thin film bounded by finite media, terminated at shorting planes situated parallel to and a long distance from the film surfaces. The results obtained with this model are checked against previous calculations for normal incidence onto a waveguide-air endface. For nonnormal incidence upon the interface between two waveguides, various interesting phenomena such as guided-wave equivalents of Brewster's angle, multiple cutoff angles for both guided waves and radiation fields, and intermode conversion are investigated numerically.

1. INTRODUCTION

The reflection and transmission characteristics of guided waves incident upon the interface between two waveguides or the endface of a waveguide are problems of continuing interest in guided-wave technology. Much of the previous work has centered on understanding (1) oscillation in semiconductor lasers[1–7] and their radiation patterns and (2) butt coupling of waveguides to other waveguides and to fibers,[3,9] both of which involve normal incidence upon the interface. With the recent interest in bistability and similar all-optical operations in integrated-optics structures, the guided-wave endface reflectivity determines the finesse of a guided-wave cavity and hence the critical power required for switching.[10,11] There are also other interesting questions for nonnormal guided-wave incidence, specifically whether there are guided-wave equivalents of Brewster phenomena and whether new effects that are unique to guided waves occur. We address these questions by calculating, for a number of cases, the reflection and transmission coefficients of the incident guided-wave mode, the fraction of power converted into other guided-wave modes, and the fraction of energy radiated out of the guided modes.

Similar guided-wave interface problems have been treated for normal incidence in the past[4–7,12–22] by using a variety of analytical techniques. For example, for small transverse discontinuities, a simple and effective approximation has been derived by Marcuse.[13] For arbitrarily large transverse discontinuities for which appreciable coupling takes place to all of the guided waves of the waveguide and to the continuous radiation spectrum, the boundary conditions along the transverse interface yield a set of integral equations. One approximation is to solve these equations by the conventional Neumann series.[6] Another is to discretize the continuous radiation spectrum, for example, by expanding it in terms of Laguerre functions[7,12,16] or Hermite Gaussian functions[21] with an adjustable width parameter. The radiation-wave continuum can also be discretized by introducing boundaries parallel to the film surface to limit the physical system

in one dimension.[17] For such a discretized mode spectrum, there are several ways to solve this set of infinite linear equations. For example, the variational technique[12,21] and the least-squares boundary-residual[7] method have been used.

In this paper we use both a boundary-residual method and a point-matching method, together with a discretized mode spectrum, to examine the reflection and mode conversion of TE and TM guided waves incident (1) at 90° upon the endface of a waveguide and (2) at variable angles of incidence upon an interface between two waveguides. In order to verify the validity of this model, comparison is made first with previous calculations in the limited number of cases in which it is possible. For example, for TE modes normally incident upon the waveguide–air interface, we obtained behavior similar to that reported by Pudensi et al.[21] and Ikegami.[22] using variational techniques for the identical waveguide system. However, for the TM case, the conversion coefficients into other guided waves and the radiation losses on reflection were found to be larger than reported in those two papers. We further examine the model by verifying that the results are only weakly dependent on the distance between the shorting planes.

In subsequent calculations we investigate a number of similarities between plane-wave and guided-wave reflection phenomena. These include Brewster's angle, reflectivity minima for radiation through endfaces, and Fresnel phenomena, including guided-wave and radiation field cutoffs.

2. THEORY

The physical system of interest is shown in Fig. 1(a), and the model that we choose to approximate it is shown in Fig. 1(b). As discussed before, the principal difference between the two is the introduction of shorting planes above ($z = d$) and below ($z = -d$) the thin-film boundaries. For guiding to be possible, the film index n_f is chosen to be larger than that of the cladding (n_c) and substrate (n_s), and the film thickness is